

Operational Status of the International Space Station Plasma Contactor Hollow Cathode Assemblies

July 1, 2001- May 31, 2013

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The International Space Station has onboard two Aerojet Rocketdyne developed plasma contactor units that perform the function of charge control. The plasma contactor units contain NASA Glenn Research Center developed hollow cathode assemblies. NASA Glenn Research Center monitors the on-orbit operation of the flight hollow cathode assemblies. As of May 31, 2013, HCA.001-F has been ignited and operated 123 times and has accumulated 8072 hours of operation, whereas, HCA.003-F has been ignited and operated 112 times and has accumulated 9664 hours of operation. Monitored hollow cathode ignition times and anode voltage magnitudes indicate that they continue to operate nominally.

I. Introduction

The International Space Station (ISS) power system is designed with high voltage solar arrays operating at output voltages of typically 140-160 V.¹ The power system is configured with a “negative ground” that electrically ties the habitat modules, structure, and radiators to the negative tap of the solar arrays. As a result of the electrical configuration and the plasma current balance, early analyses indicated that the habitat modules, structure, and radiators may float to voltages as high as 120 V with respect to the ambient space plasma.¹ Furthermore, given the large negative floating potentials, there exist the probability for deleterious interactions of the ISS and the space plasma. In 1992, a decision was made to baseline a plasma contactor on the ISS, from a variety of solutions, as a means to mitigate these interactions.² A plasma contactor establishes a low impedance plasma bridge to control the spacecraft potential relative to the local space plasma. Figure 1 illustrates the current path enabled through a plasma contactor. The plasma contactor unit (PCU) consists of a hollow cathode assembly (HCA), power electronics unit (PEU), and gas feed system (GFS). The entire unit is contained within an avionics box referenced as the orbit replaceable unit (ORU).¹ The HCA within each PCU generates the electrons required for ISS charge control, and is electrically tied to the negative single point ground of the ISS main truss segment. The HCA consists of a low-work function insert for electron emission, a body tube with a heater, and an electrical isolator. During HCA operation, a continuous xenon flow of 6.0 to 7.5 sccm is maintained, a 3.0 A current to the anode is emitted, and the HCA emits to the space plasma for space charge control.

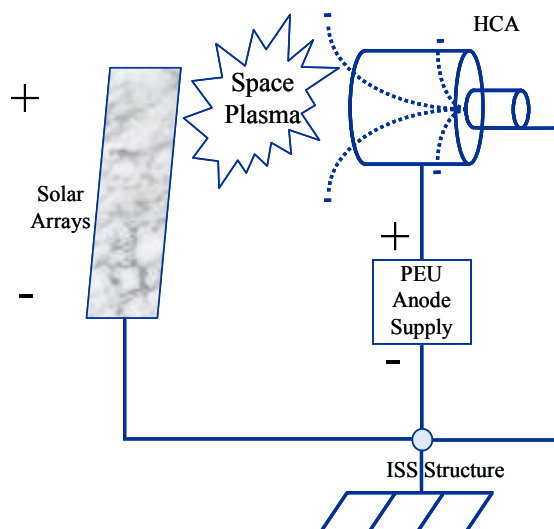


Figure 1. ISS simplified plasma contactor unit electrical schematic.

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NASA Glenn Research Center (GRC) developed and delivered the flight HCAs, shown in Figure 2, for integration into the PCUs. The NASA GRC HCA development program included manufacture, test, and installation of engineering, qualification, and flight model HCAs according to the program requirements.^{3,4} This included long duration testing of the devices to meet the 18,000 operational hours requirement. A 28,000+ hours operation test⁵ and a 19,000+ hours operation test⁶ were among the tests performed in support of this goal. Table 1 presents the final status of the life tested hollow cathode assemblies where all life tests were terminated voluntarily. In addition, a high fidelity development model HCA attained 32,000 successful ignition cycles, demonstrating the ISS requirement of 6,000 ignition cycles with at least 99% reliability.⁷ HCA heater testing was also conducted to determine the cyclic life capability of the heater, which was found to be around 12,000 cycles.⁸ Finally, prior to installing the HCAs in their PCUs, the flight HCAs underwent multi-step performance acceptance tests at NASA GRC.^{1,3,4,6,7,8} The HCAs were subsequently integrated into the PCU ORUs at the flight contractor site where the PCU ORUs



Figure 2. Flight hollow cathode assemblies.

Table 1. Summary of accumulated hours and number of ignitions for life-tested hollow cathodes.

Unit	Accumulated Hours	Accumulated Ignitions
HCA-003 ^a	12,415	38
HCA-006 ^a	8,030	1
HCA-010 ^a	15,876	4424
HCA-013 ^a	18,873	59

^a Test terminated voluntarily

underwent acceptance-level environmental testing. Afterwards, the PCU ORUs were shipped to NASA GRC where they underwent further testing to verify the operability of the HCA and the PCU to assess the plasma clamp voltage. These tests established that the HCA and PCU were fully functional and capable of emitting the required electron current within the 20 V potential requirement. The current emitted by the HCAs to the space plasma, and which is collected by the ISS solar arrays, is referred to as the clamping current. The PCU ORUs were subsequently shipped to NASA Kennedy Space Center

(KSC) for integration to the ISS Z1 structure and launch.

There were two initial flight models, PCU FM01 and PCU FM02, which incorporated the HCAs designated HCA.001-F and HCA.003-F, respectively. These PCUs, shown in Figure 3, were developed by the Rocketdyne Division, part of the Boeing Company at that time. They were delivered to the ISS aboard the Space Shuttle Discovery in October of 2000. These two PCUs are co-located on the ISS Z1 truss as shown in Figure 3.

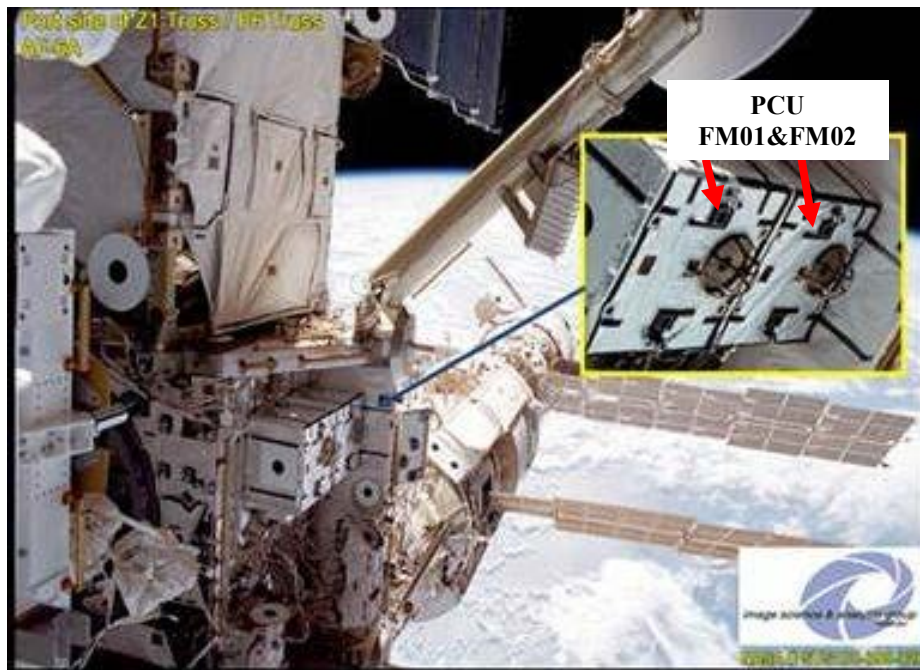


Figure 3. Location of plasma contactor on the Z1 truss.

For a third flight model, PCU FM03, NASA GRC personnel installed HCA.006-F into the PCU at Aerojet Rocketdyne's Canoga Park facility in April 2008. A series of tests were performed at NASA GRC vacuum facility 5 (VF5) on PCU FM03, shown in Figure 4, in the summer of 2008. The tests included fifteen ignition cycle tests, a clamp voltage test, and a 24 hour test to confirm HCA stable operation.⁹ PCU FM03 was launched on STS-129, on November 16, 2009, on the External Logistics Carrier 1 (ELC1). The unit's latch valves were closed prior to launch, at L-85 hours. On November 18, 2009 the unit was moved from the Space Shuttle cargo bay to the ISS as is shown in Figure 5. Currently, ELC1 is stored on the P3 (port) truss of the ISS. PCU FM03 will not be activated until 2028 when PCU FM02 is expected to run out of xenon expellant.

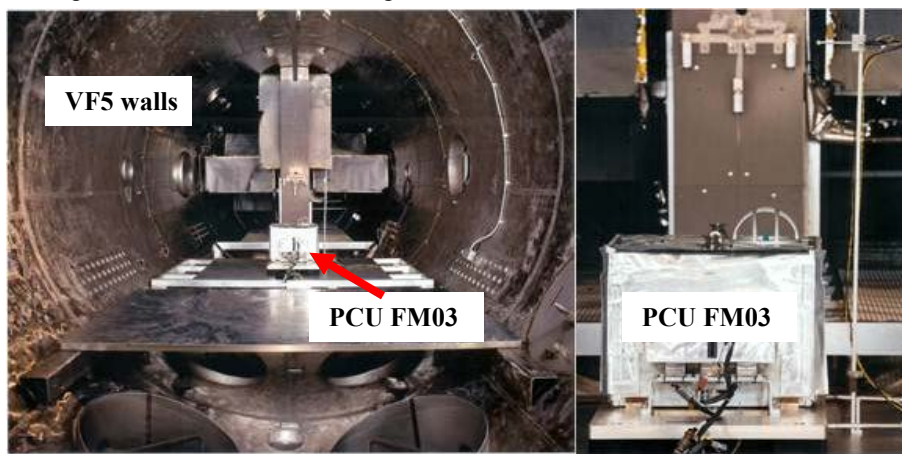


Figure 4. Photograph of PCU flight model 3 inside VF5 at NASA GRC.



Figure 5. Relocation of ELC1 from Shuttle cargo bay to ISS.

II. On-Orbit Operation of PCU FM01 and PCU FM02

The first two flight HCA units installed aboard the ISS, HCA.001-F in PCU FM01 and HCA.003-F in PCU FM02, are currently in operation. On October 16, 2000, the first ignition of a PCU aboard the ISS took place. The PCUs now typically operate during extra-vehicular activities (EVAs), shuttle docking, or as deemed necessary. During spacewalks, the two PCUs are operated simultaneously for redundancy.

The on-orbit status and health of the HCAs are assessed by monitoring the ignition time and anode voltage. The ignition time is defined as the time between the initiation of the cathode warm-up procedure (i.e, current flow to heater) to the detection of anode current (current between the cathode and keeper plate) indicating plasma formation between the cathode and anode. Increases in the ignition time and/or anode voltage may indicate hollow cathode performance degradation. This degradation can occur due to changes in the emitter surface chemistry, depletion of the emitter impregnate material, heater degradation, and physical changes to the cathode/keeper orifice plate configurations.^{5,6,7} The data from operating the HCAs in the time period from July 1, 2011 to May 31,

2013 will be presented in the next two sections. HCAs operational status results from ground-based tests and aboard the ISS prior to July 1, 2011 have been presented earlier.⁹⁻¹⁵

Prior to the Space Shuttle fleet retirement in July of 2011, the PCUs were operated for extended durations (100-200 hrs) when the Space Shuttle was docked to the ISS and there were plans for multiple spacewalks during the mission. However, starting with the last Space Shuttle mission (Atlantis STS-135), the PCUs were only operated for durations of 10 to 15 hours each during spacewalks. Table 2 in Appendix 1 lists the spacewalks that took place since July 1, 2011.

A. Hollow Cathode Assembly HCA.001-F on PCU FM01

Operational details of HCA.001-F are presented in Table 3. During the time period from July 1, 2011 to May 31, 2013, HCA.001-F was ignited 8 times (segments 116-123) and operated for a total duration of 106.8 hours. For the flight HCAs, a “segment” is defined as the period of time between HCA ignition and until it is commanded off and the emission current reaches zero. At the end of segment 123, the total accumulated operating time was 8072 hours. HCA.001-F ignition times for segments 116-123 were between 3.6 and 4.7 minutes as presented in Figure 6 and Table 2. These ignition times are consistent with previous segments ignition times. Figures 7, 9, and 11 present the anode voltage profiles during segments 116, 120, and 123, respectively. Figures 8, 10, and 12 present the clamping current profiles during segments 116, 120, and 123, respectively. The profiles shown in Figures 7-12 are representative of typical HCA.001-F operation.⁹⁻¹⁵ Results in Table 3 show that the anode voltage range is approximately 13.4-15.7 V; the higher voltage occurs after HCA ignition (typical after ignition) and drops from that point to the nominal operating value of 13 to 14 V.⁶ Table 3 shows that the largest operating clamping current is 0.176 A; clamping current readings below 0.018A are considered noise.

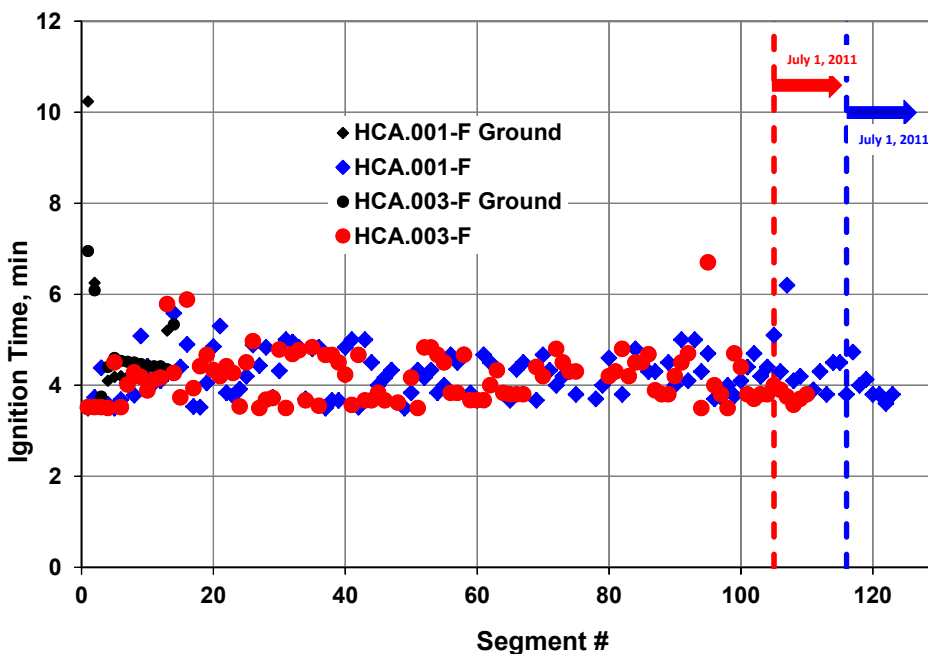


Figure 6. Ignition times for all ISS flight data segments.

Table 3. HCA.001-F operation details for period from July 1, 2011 to May 31, 2013.

Ignition/Operating Segment Number	Operation Start Date	Duration, hours	Ignition Time, minutes	Accumulated Operating Hours, hrs	Anode Voltage Range, V	Clamping Current Range, A
116	July 12, 2011	16	3.8	7981.2	13.7-14.8	0-0.129
117	August 3, 2011	13.1	4.7	7994.3	13.6-15.5	0-0.080
118	February 16, 2012	13.2	4.0	8007.5	13.7-15.6	0-0.076
119	August 20, 2012	12.8	4.1	8020.3	13.5-15.7	0-0.176
120	August 30, 2012	11.8	3.8	8032.1	13.4-14.7	0-0.117
121	September 5, 2012	11.8	3.8	8043.9	13.4-14.6	0-0.135
122	November 1, 2012	13.9	3.6	8057.8	13.5-15.6	0-0.064
123	April 19, 2013	14.2	3.8	8072.0	13.4-15.7	0-0.111

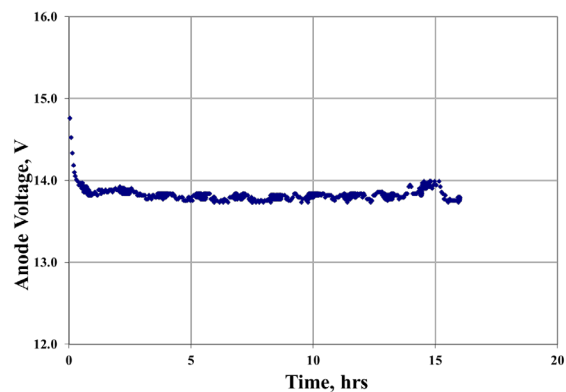


Figure 7. HCA.001-F anode voltage profile during segment 116.

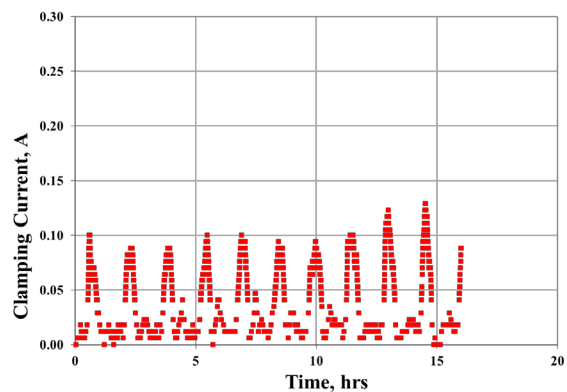


Figure 8 HCA.001-F clamping current profile during segment 116.

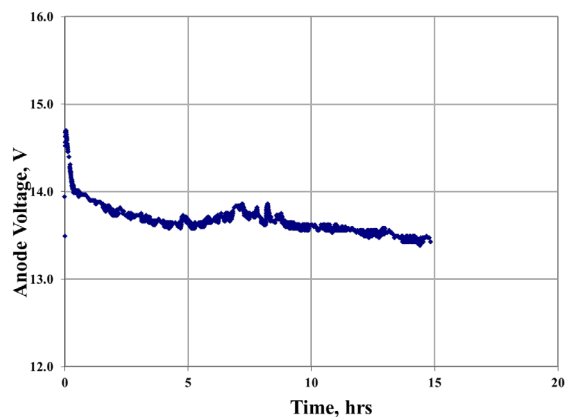


Figure 9. HCA.001-F anode voltage profile during segment 120.

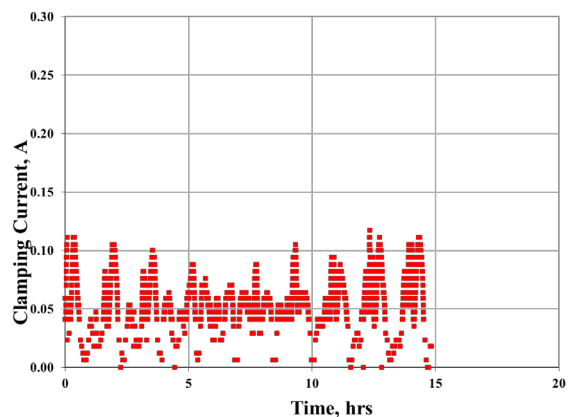


Figure 10. HCA.001-F clamping current profile during segment 120.

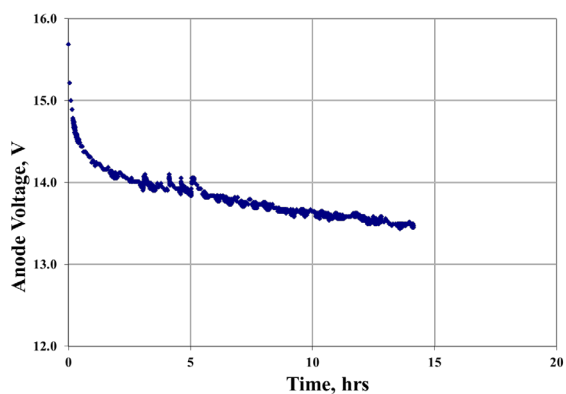


Figure 11. HCA.001-F anode voltage profile during segment 123.

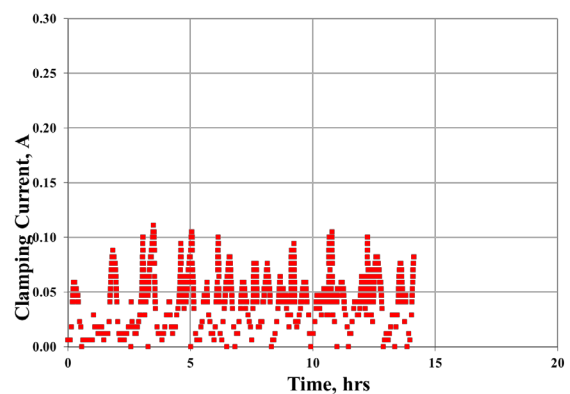


Figure 12. HCA.001-F clamping current profile during segment 123.

B. Hollow Cathode Assembly HCA.003-F on PCU FM02

Operational details of HCA.003-F are presented in Table 4. During the time period from July 1, 2011 to May 31, 2013, HCA.003-F was ignited 8 times (segments 105-112) and operated for a total duration of 108.9 hours. At the end of segment 112, the total accumulated operating time was 9664.4 hours. HCA.003-F ignition times for segments 105-112 were between 3.6 and 4.5 minutes. These ignition times are consistent with previous segments ignition times. Figures 13, 15, and 17 present the anode voltage profiles during segments 105, 109, and 112, respectively. Figures 14, 16, and 18 present the clamping current profiles during segments 105, 109, and 112, respectively. The profiles shown in Figures 13-18 are representative of typical HCA.003-F operation.⁹⁻¹⁵ Results in Table 4 show that the anode voltage range is approximately 13.1-16.4 V; the higher voltage occurs after HCA ignition (typical behavior) and drops from that point to the nominal operating value of 12 to 13 V.⁶ Table 4 shows that the largest operating clamping current was 0.205 A. For the clamping current, readings below 0.018A are considered noise.

Table 4. HCA.003-F operation details for period from July 1, 2011 to May 31, 2013

Ignition/Operating Segment Number	Operation Start Date	Duration, hours	Ignition Time, minutes	Accumulated Operating Hours, hrs	Anode Voltage Range, V	Clamping Current Range, A
105	July 12, 2011	16.2	4.0	9571.7	13.8-14.9	0-0.130
106	August 3, 2011	13.4	3.9	9585.1	13.3-14.6	0-0.115
107	February 16, 2012	13.0	3.8	9598.1	13.3-14.6	0-0.082
108	August 20, 2012	12.3	3.6	9610.4	13.3-16.4	0-0.205
109	August 30, 2012	12.8	3.7	9623.2	13.4-14.7	0-0.170
110	September 5, 2012	12.1	3.8	9635.3	13.6-15.1	0-0.176
111	November 1, 2012	14.1	4.2	9649.4	13.5-15.7	0-0.105
112	April 19, 2013	15.0	4.5	9664.4	13.1-15.3	0-0.135

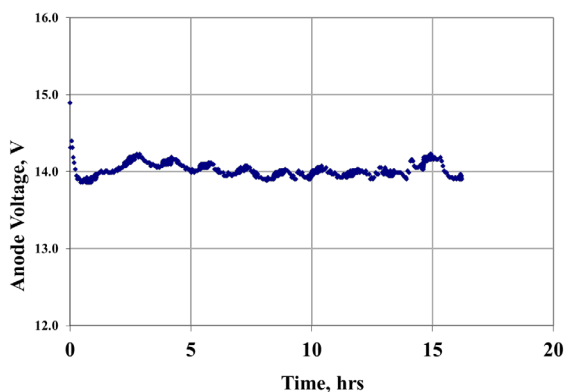


Figure 13. HCA.003-F anode voltage profile during segment 105.

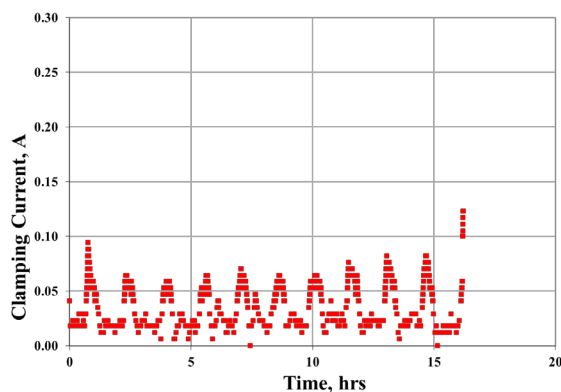


Figure 14. HCA.003-F clamping current profile during segment 105.

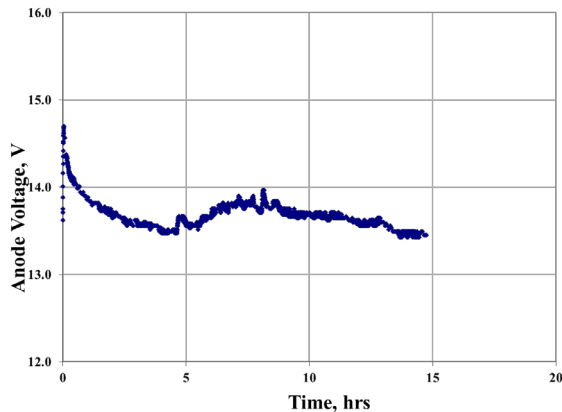


Figure 15. HCA.003-F anode voltage profile during segment 109.

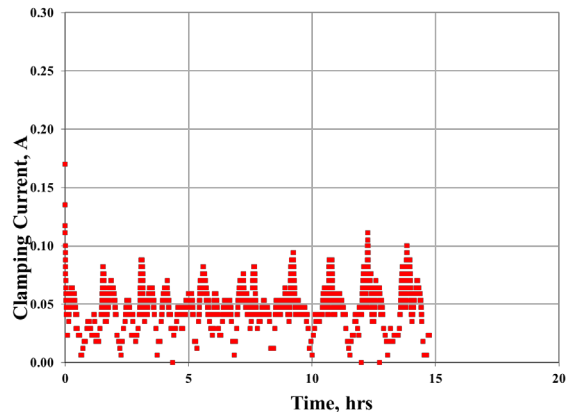


Figure 16. HCA.003-F clamping current profile during segment 109.

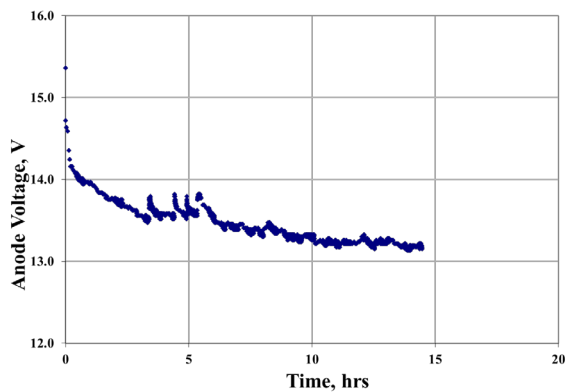


Figure 17. HCA.001-F anode voltage profile during segment 112.

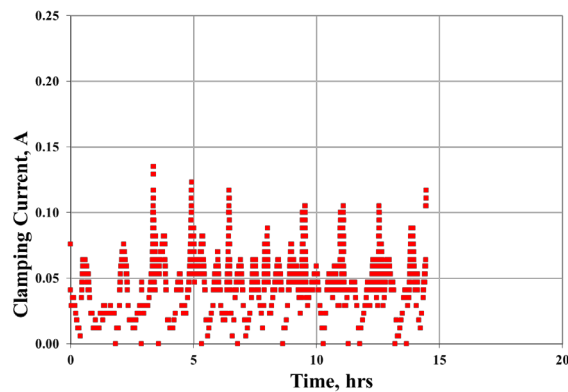


Figure 18. HCA.001-F clamping current profile during segment 112.

III. Conclusion

NASA GRC continues to play a critical role in supporting the ISS PCUs through monitoring hollow cathode assembly operation aboard the ISS. As of May 31, 2013 HCA.001-F has been ignited 123 times and has accumulated 8072 hours of operation, whereas, HCA.003-F has been ignited 112 times and has accumulated 9664.4 hours of operation. During this time period, HCA.001-F and HCA.003-F were operated for a total duration of 106.8 and 108.9 hours, respectively. The monitored ignition time, anode voltage, and clamping current values during the period from July 1, 2011 to May 31, 2013 indicate that the hollow cathode assemblies continue to operate and function consistent with their respective ground-based tests and earlier operation on the ISS.

References

- ¹ Patterson, M.J., et al., "Plasma Contactor Development for Space Station," IEPC 93-246.
- ² Moorehead, R.W., Deputy Director, Space Station Freedom Program and Operations, communications to Work Packages 1-4 Directors, April 3, 1992.
- ³ Patterson, M.J., et al., "Plasma Contactor Technology for Space Station Freedom," AIAA 93-2228.
- ⁴ Patterson, M.J., Verhey, T.R., Soulas, G.C., and Zakany, J., "Space Station Cathode Design, Performance, and Operating Specifications," IEPC 97-170.
- ⁵ Verhey, T.R., "28,000 Hour Xenon Hollow Cathode Life Test Results," IEPC 97-168.
- ⁶ Soulas, G.C., "Multiple Hollow Wear Testing for the Space Station," AIAA 94-3310.
- ⁷ Zakany, J., Pinero, L. "Space Station Cathode Ignition Test Status at 32,000 Cycles," IEPC 97-167.

- ⁸ Soulas, G.C., "Status of Hollow Cathode Heater Development for the Space Station Plasma Contactor," AIAA 94-3309.
- ⁹ Kamhawi, H., Patterson, M.J., and Dalton, P., "On the Operational Status of the International Space Station Plasma Contactor Hollow Cathodes," AIAA 2009-5092.
- ¹⁰ Carpenter, C.B., "Comparison of On-Orbit and Ground Based Hollow Cathode Operation," AIAA 2002-4098.
- ¹¹ Carpenter, C.B., "Comparison of On-Orbit and Ground Based Hollow Cathode Operation," AIAA 2003-5145.
- ¹² Carpenter, C.B., "On the Operational Status of the ISS Plasma Contactor Hollow Cathodes," AIAA 2004-3425.
- ¹³ Kamhawi, H., and Patterson, M.J., "On the Operational Status of the International Space Station Plasma Contactor Hollow Cathodes," AIAA 2005-3676.
- ¹⁴ Kamhawi, H., and Patterson, M.J., "On the Operational Status of the International Space Station Plasma Contactor Hollow Cathodes," AIAA 2007-5190.
- ¹⁵ Kamhawi, H., Patterson, M.J., and Dalton, P., "Update on the Operational Status of the International Space Station Plasma Contactor Hollow Cathodes," AIAA 2011-5990.

Appendix 1

Table 2: List of Spacewalks since July 1, 2011⁵

Mission	Date	Spacewalk Duration	Description	PCU Operated
Expedition 28 EVA1	July 12, 2011	6 hrs 31 mins	Last spacewalk performed while the Space Shuttle was docked to the ISS. During spacewalk a failed pump module was retrieved and MISSE 8 experiment was also deployed.	Yes
Expedition 28 EVA2	August 3, 2011	6 hrs 23 mins	Spacewalkers installed: laser communication equipment, a student experiment, and the BIORISK experiment.	Yes
Expedition 30 EVA1	February 16, 2012	6 hrs 15 mins	Spacewalkers repositioned the Strela 1 equipment crane in preparation for the undocking of the Pirs docking compartment. In addition an experiment was retrieved and a new one installed.	Yes
Expedition 32 EVA1	August 20, 2012	5 hrs 51 mins	Spacewalkers relocated the Pirs docking compartment to prepare for its undocking in preparation for the docking of the Russian Multipurpose Laboratory Module. Other tasks were also performed including deployment of small satellite to track space debris.	Yes
Expedition 32 EVA2	August 30, 2012	8 hrs 17 mins	Spacewalkers replaced the Main Bus Switching Unit (MBSU) and they also rerouted some cables.	Yes
Expedition 32 EVA3	September 5, 2012	6 hrs 28 mins	Spacewalkers installed the MBSU. Astronaut Sunita Williams broke Peggy Whitson's record for most time spacewalking by a woman.	Yes
Expedition 33 EVA1	November 1, 2012	6 hrs 38 mins	Spacewalkers reconfigured and isolated a leak in the ammonia cooling system.	Yes
Expedition 33 EVA1	April 19, 2013	6 hrs 38 mins	Spacewalkers installed the Obstanovka plasma waves experiment, replaced a faulty retro-reflector, and retrieved the BIORISK experiment.	Yes
Expedition 35 EVA1	May 11, 2013	5 hrs 30 mins	Spacewalkers inspected and replaced a pump flow control subassembly.	No

⁵ http://en.wikipedia.org/wiki/List_of_ISS_spacewalks#2011